A one hertz continuous pellet generator for controlled fusion application

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Pellet generators are needed to fuel long pulse tokamak plasmas. For this purpose, an experiment was carried out, using a new apparatus, in order to demonstrate the feasability of a pellet generator functioning with magnetic refrigeration. This new cooling solution seems well adapted to continuous operation and the principle of a 1 Hz pellet generator is presented.

1. INTRODUCTION

Fusion tokamaks operation can be associated with H_2, D_2 or T2 pellets injection for plasma refuelling and density profile control, or for plasma cleaning by impurities removal. For each specific duty, solid particles have to be produced and then accelerated in a safe and repetitive process. For speed in the 1000 ms^{-1} range, good results can be obtained with centrifuge injectors [1]. To provide deeper pellet penetration, one stage light gas guns have to be used up to about 2000 ms^{-1} [2], and two stage if higher speeds are needed [3]. Through this technique unprotected pellets have recently been launched up to 3400 ms^{-1} in a very reliable way [4] .

For ice pellets formation several choices were investigated:

The extrusion technique in which a soft solid is pushed by a piston through a calibrated orifice is basically discontinuous up to the point where a cylinder has to be preloaded [5-6-7].

The same drawback appears for mechanical punching of ice previously deposited around a cylinder [8] , therefore, one is less confindent about the long term behaviour of associated mechanisms.

The in situ condensation technique [9], mainly appreciated for its static process, is to slow for continuous operation. Such a condensation method can only apply with a lot of simultaneously working cells associated with a pellet storage.

Another process has been investigated with the aim to introduce a new cooling solution well adapted to continuous operation by means of simple and reliable mechanisms.

2. COOLING BY PARAMAGNETIC MATERIAL DEMAGNETISATION

The well known adiabatic demagnetisation cooling is based upon the paramagnetic materials in which elementary magnetic moments can be oriented by an applied external field, whilst no magnetisation is observed at zero-field. The external field provides an easy means to reversibly control the material entropy giving the capability to absorb or exhaust heat.

For a reversible process, the associated heat quantity can be written

$$Q = \int T \, dS$$

Q being positive or negative with respect to the sign of the entropy variation.

In the temperature range in which hydrogen isotopes can be frozen a well adapted material is known as Europium Sulfide (EuS). The EuS entropie diagram S (T) is given in figure 1 by taking the residual field (applied field - demagnetising field of the EuS) as a parameter [10]. In figure 1, three possible transformations can be obtained starting from point 1 where initial conditions can be taken as an example, with T = 19K and B = 2,5T (applied field = 3T). Transformation 1 to 2 is obtained when the external field is removed from the material thermally insulated from outside. With no possible heat exchange

TdS = 0 means dS = 0.

In such a case by adiabatic or isentropic evolution, the temperature will be lowered to about 14K. Transformation 1 to 3 corresponds to field removal by keeping the temperature constant. That is possible if the material is in perfect contact with a medium at 19K from which a heat quantity $Q_{1,3} = T \Delta S_{1,3} = 2.2 J / cm^3$ will be removed.

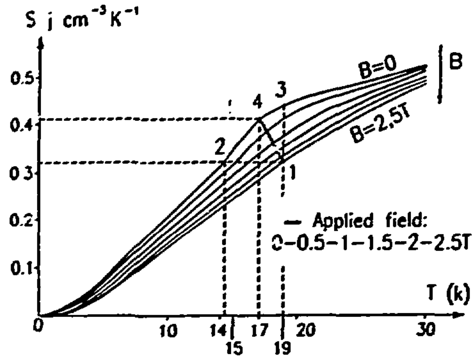

Figure 1. EuS Diagram S = f(T)

All other intermediate alternatives can be obtained with, for example the 1-4 process in which the material receives the heat quantity $Q_{1,4} = T \Delta S_{1,4} = 1.64 J / cm^3$ even with a temperature decreasing to 17K. If the 1 to 4 process is imposed on a EuS sample immersed in a 19K liquid deuterium bath boiling at reduced pressure, the demagnetisation operation will induce a material cooldown to a temperature lower than needed for D_2 freezing. The frozen D_2 volume will be limited by the removed heat quantity.

3. EXPERIMENTAL SET UP

The potentiality of magnetic cooling has been experimentally investigated to control how it could be implemented to produce D_2 or T_2 pellets. The experimental arrangement is represented in figure 2. A Europium Sulfide ring is encapsulated in an insulating material with a cylindrical hole drilled in the center. The size of the EuS sample was:

External diameter = 23.4 mm
Internal diameter = 4.1 mm
Thickness = 7.6 mm

Corresponding to a quantity of EuS of 3.1 cm^3 volume and 16.4 g. mass. The central hole Ø = 4.1 mm - L = 7.6 mm corresponds to 100 mm^3 volume of liquid deuterium which could be frozen. This assembly is immersed in a liquid deuterium bath boiling at 19K over 193 mb.

The deuterium cryostat is surrounded by a liquid helium cryostat with a superconducting solenoid in it. The field profile on the solenoid axis can be adjusted. Experiments were performed with typical values such as:

In the middle plane, 3 Tesla applied field to get 2.5 Tesla residual field in the EuS sample.

16 cm above the middle plane, 0.5 Tesla applied field for 0.2T residual field.

By means of a linear actuator the EuS sample can be moved along the solenoid axis by controlling the speed or the position in the range between 0 and 16 cm from the centre of the coil.

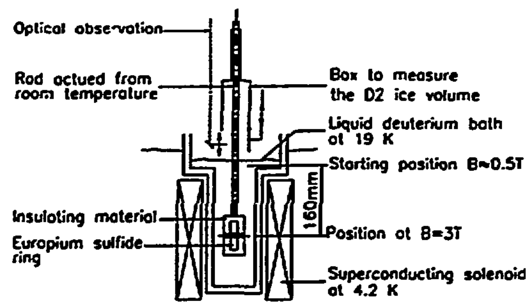

Figure 2. Experimental Arrangement

The D_2 liquid level has to be adjusted to ensure that the 4 mm hole is permanently immersed. The experiment starts by raising the magnetic field with EuS at the top location. When the EuS is moved down the middle plane, isothermal magnetisation dissipates a heat quantity which evaporates some of the liquid Deuterium. After equilibrium, EuS is moved up at 7 mm/s over 16 cm (23 seconds) then kept at rest for 36 seconds. D_2 ice frozen inside EuS was measured to be 37 mm^3 after 24s., then 87 mm^3 after 60s. D_2 ice quantity was estimated after being warmed up by gas volume measurement. The EuS temperature variation was recorded providing the means to calculate the energy balance all along the process, in this way, the following heat breakdown was estimated for a 87 mm^3 volume of D_2 ice

Heat removed by EuS = 6.1 J

Heat needed for D_2 freezing = 0.8 J

Losses through solid insulator = 5.2 J

Losses by convection in the D_2 channel of 4.2 mm diameter = 0.1 J

Such an experiment shows the capability to produce 4 mm D_2 pellets within 60 seconds. This time duration is mainly controlled by the existing ΔT between EuS and the liquid-solid transition temperature. With a specially designed solenoid a more efficient insulator, and an adequate EuS quantity, a smaller time could be obtained in the range 30 to 40 seconds. From this result a 1 Hz continuous pellet generation can be proposed.

4. TENTATIVE SKETCH OF A ONE HERTZ GENERATOR

Figure 3 shows a continously rotating chain made up of active cells located every 3 cm. The lower part of the chain is immersed in liquid D_2 and around one straight side a superconducting solenoid provides the required field. EuS isothermal magnetisation is obtained by penetrating to the lower side of the magnet.

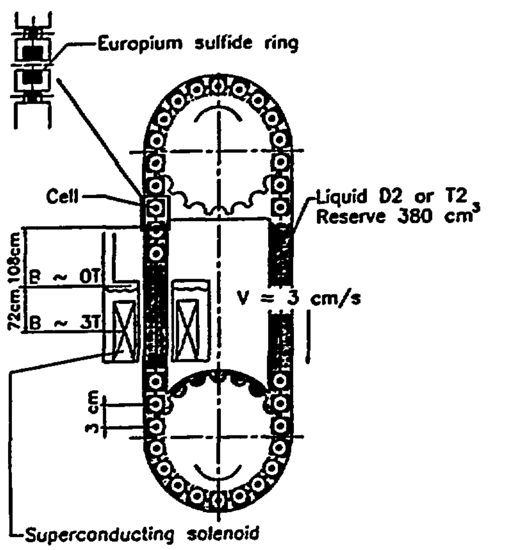

Figure 3. Sketch of one Hertz generator

Demagnetisation and ice freezing is obtained at the upper part of the magnet where the liquid level is carefully controlled. To produce one pellet per second with a pitch of 3 cm, the velocity of the chain displacement only has to be 3 cm/s^{-1}. In such a case, the same behaviour that was tested in the previous experiment will be obtained for a movement of 72 cm in the field gradient, then a movement 108 cm in the liquid column at zero-field. A better optimisation seems possible to reduce the needed time and then the total length to about 1 m.

After pellet formation, the active cells arise in the gaseous region where ice can be easily unloaded, as shown in figure 4. By forcing the paramagnetic material through a permanent magnet providing about 0.5 Tesla, it will result in a temperature rise of about 2K sufficient enough to unglue the ice. A linear actuator can be ordered to introduce the pellet through a transporting duct where a guillotine gate opens with the right timing reducing the gas leakage. The final cooling of the preformed pellet is obtained by sublimation in the transporting duct under vacuum. To cool a pellet from 18K to about 5K, only 4% of the initial mass has to be evaporated. As can be seen from this very preliminary approach, a one hertz pellet generator cannot be considered as a serious challenge. All the moving parts are submitted to quite low stresses and low speed permanent displacement and could be obtained by using very reliable solutions able to fulfill the fusion tokamak specifications. In the worst case of tritium operation to minimise the inventory

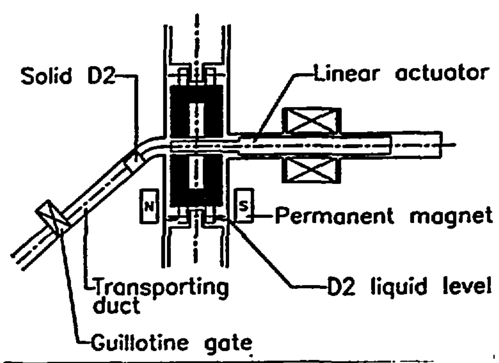

Figure 4. Solid D_2 unloading station

of radioactive isotope the stored volume of the liquid bath could be kept in the range of a few hundred cubic centimeters. The last problem to be solved is the way to connect the pellet generator with the associated launcher. Repetitive loading of a one or two stage gas gun could be considered to get high speed injector but in the range of 1000 m/s the supply of centrifuge injector seems more accessible as a first step.

5. CONCLUSION

A new way has been tested for D2, T2 pellets formation. By magnetic cooling of a paramagnetic material, 4 mm diameter D2 pellets have been produced. From this promising method, continuous and reliable pellet generators seems accessible even for tritium operation in the few hertz range.

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